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CRITERIA OF EFFECTIVENESS OF SOIL STABILIZATION BY GROUTING (KR--ETC(U)
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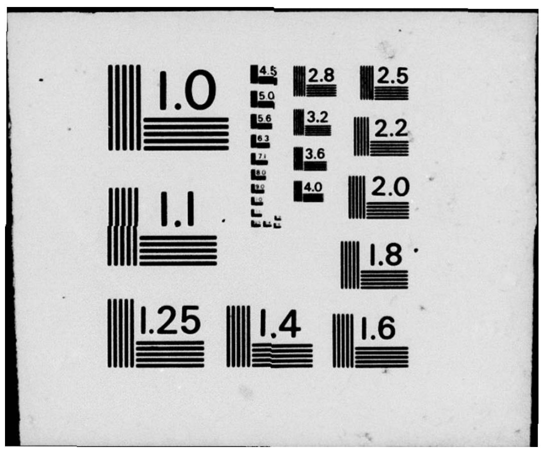
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J. Plch

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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CRITERIA OF EFFECTIVENESS OF SOIL STABILIZATION BY GROUTING

Prague INZENYRSKE STAVBY (Engineering Constructions) in Slovak, No 1, 1974, pp 29-32

[Article by Engr Jaromir Plch, CSc., Research Institute for Engineering Constructions in Bratislava]

[Text] The article presents a critical analysis of factors which affect the economical aspects of grouting (injection).

Some Technical-Economic Questions of Soil Grouting

The present technical development of grouting of soil shows that in the case of soils which are less permeable, it is appropriate to grout them by using new injection substances, for example macromolecular substances. However, the price of these new materials is substantially higher than the price of classic materials, which include today for example cement suspensions or -- to a certain extent -- also solutions of water glass. This trend exists all over the world, as shown in the table of relative prices of individual material (Table 1) according to data obtained from France (Cambefort 1964), England (Moller 1964), USSR (Adamovic 1973) and Czechoslovakia (Plch 1971). But even in terms of absolute prices, the trends in Czechoslovakia do not differ from those in foreign countries (Table 2 shows certain prices from 1970, which were determined directly by recomputation based on the rate of exchange).

The relatively high prices of new injection materials cost a certain amount of distrust, especially on the part of investors and project engineers with regard to the future development of injection material and the method of grouting in general. However, let us examine how the price of injection materials is projected in the price of 1 cubic meter of the injected soil, because such index alone is objective, especially when it is a question of the final effect of grouting, which means above all stabilization. Let us examine further what the criteria are of the effectiveness of grouting, when we evaluate the entire physical process of grouting, in other words basically the flow from the moment of drilling, while taking in consideration the rheological properties of the injection materials.

Grouting of coarse-grained soil with coefficient of permeability $K > 2.10^{-2}$ centimeters per second by means of stable suspensions is not a technical or economic problem today. A combination of technical-economic problems arises only when the earth is less permeable. According to an idealized technical point of view, one can grout by a chemical solution basically any kind of soil through which water flows, which means also clay. However, in reality there are limitations in this case in the same way as in the case of suspensions by the dimensions of the colloidal particles (water glass), or by the dimensions of the macromolecules and their behavior during the flow below a certain lower limit, which is the coefficient of permeability of the order of $K = 10^{-6}$ centimeters per second. This means that within the limits of $K = 10^{-2}$ centimeters per second to $K = 10^{-6}$ centimeters per second the grouting is technically possible, but the effectiveness of the grouting is shown altogether only by an economic analysis. And this indicates clearly that grouting has become an industrial method even in this area.

Table 1. Comparison of Relative Prices of Injection Substances

	a Hmota	b Francúzsko	c Anglicko	d ZSSR	e ČSSR
1	Cementová suspenzia	1	1	1	1
2	Cement – íl (2 : 3)	0,25	0.25	0,25	–
3	Ílocement (5 : 1)	–	–	–	0,4
4	Ílochemická suspenzia	–	0,5	–	0,2÷0,4
5	Vodné sklo	1,5÷3	–	1[1])	1,4÷4,8
6	Chrómlignín	1,3÷2	–	1,5÷2,5	2,2÷3,7
7	Močovinoformaldehyd	–	–	2÷3	2,1÷7,1
8	Resorcinolformaldehyd	2,5÷10	5,6·	–	6÷15
9	Akrylamid	12÷36	6	12÷25	20
10	Furfurol	–	–	8÷10	–

Note. The data concerning waterglass are obviously influenced here by the fact that the author took in consideration only solutions of low concentration.

Key: a. Material, b. France, c. England, d. USSR, e. Czechoslovakia.
1. Cement suspension, 2. cement -- clay (2:3), 3. clay-cement (5:1),
4. clay-chemical suspension, 5. waterglass, 6. chromium lignine,
7. urea-formaldehyde, 8. resorcine-formaldehyde, 9. acrylamide,
10. furfurol.

Table 2. Prices of One Cubic Meter of Grouting Substances in Foreign Countries and in Czechoslovakia

	a Hmota	b Koncentrácia	c Cena [tis. Kčs]	d Krajina	e ČSSR f koncentrácia	g cena [tis. Kčs]
1	Cementová suspenzia	w – 0,6	0,7	USA	w = 0,5	0,7÷0,9
2	Joosten	100 %	2,4	ZSSR	–	–
3	Vodné sklo	50÷1 %	2,3÷2,9	F, K	50÷100 %	1,6÷3,5
4	Resorcinol-formaldehyd	20÷40 %	6,3÷7,0	A, F	20÷40 %	3,8÷9,5
5	Chrómlignín	40 %	2,3÷4,8	A, K	20÷40 %	1,5÷2,3
6	Akrylamid	10÷20 %	5,9÷8,1	USA, ZSSR, A, K	15 %	4÷12,5
7	Močovino-formaldehyd	30÷70 %	2,7÷6,1	ZSSR	15÷70 %	1,3÷4,6

Key: a. Material, b. concentration, c. price (in Kcs 1,000), d. country, e. Czechoslovakia, f. concentration, g. price (in Kcs 1,000).
1. Cement suspension, 2. Joosten, 3. waterglass, 4. resorcinol-formaldehyde, 5. chromo-lignine, 6. acrylamide, 7. urea-formaldehyde.

Note: A -- England, K -- Canada, F -- France, ZSSR -- Soviet Union.

It should be also noted that it is possible to grout any kind of rocks. For example, we can stabilize clay by cement suspension or by certain solutions, if we tear it up by grouting and as a result form a continuous "claquage." This method has been taken over from the oil industry, where it is used routinely for the purpose of increasing the output of the wells, and also for grouting (for example, impermeable layers were stabilized in this way by cement in 1936 in Azerbaidzhan). "Claquage" changes to a certain extent the existing criteria of the possibility of using grouting substances. However, it depends on a whole series of specific conditions, and in particular it requires great experience and well-thought-out management even in suitable cases, because the chance factor in most cases is predominant as compared to natural laws. Thin screens according to the Japanese method (Fujii 1971, Yahira 1973) represent a single-purpose application of "claquage" by a controlled process. That is why the application of "claquage" is excluded from our future considerations as a special case. We shall discuss the predominant classic method of grouting, since the injection material penetrates through the pores of the earth in a more or less continuous flow.

Method of Solving the Problem

In this part we analyze a case which occurs frequently with certain variations under the conditions which exist in Czechoslovakia. By making drills 10 meters deep in second-grade earth, we stabilize at a depth of 5 to 10 meters the earth with permeability ranging from 10^{-1} centimeters per second to 10^{-4} centimeters per second. The drills are made by sleeve pipes, with the distance of perforation apertures of 33 centimeters each. It is assumed that the grouting is done under a pressure of 5 or 10 atmospheres, and the distances of the drills in all cases are 1 to 3 meters. We shall compare rheologically similar substances which are used in Czechoslovakia in such cases, which means urea-formaldehyde resins with combined catalyzer, and waterglass with combined organic reagent. The data concerning the concentration of certain substances, the initial viscosity and strength of the grouted earth of different composition are given in Table 3.

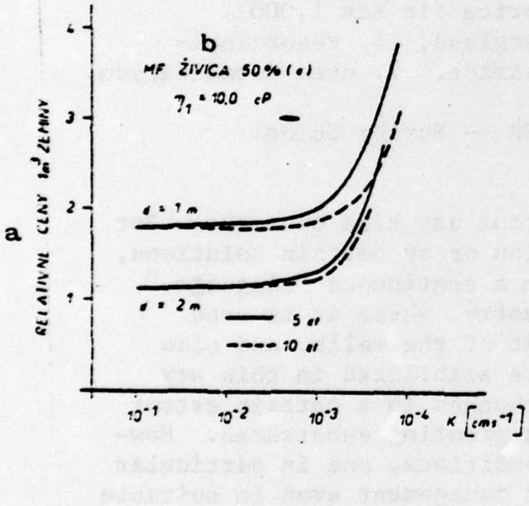

Figure 1. Dependence of the price of 1 cubic meter of stabilized earth (50 per cent of urea-formaldehyde resin) on the coefficient of permeability.

Key: a. Relative prices of 1 cubic meter of earth, b. urea-formaldehyde resin 50 per cent.

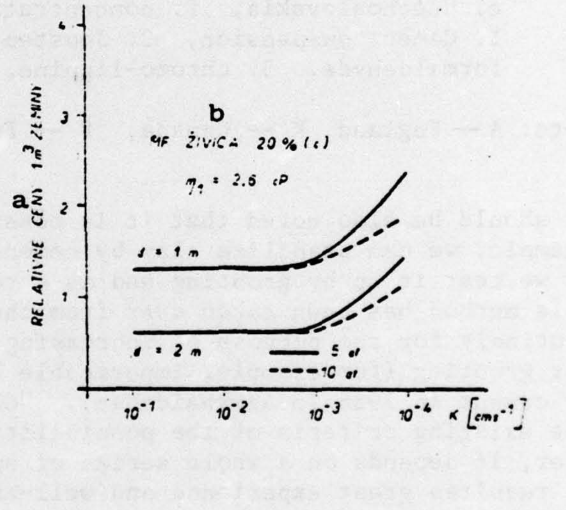

Figure 2. Dependence of the price of 1 cubic meter of stabilized earth (20 per cent of urea-formaldehyde resin) o n the coefficient of permeability.

Key: a. Relative prices of 1 cubic meter of earth, b. urea-formaldehyde resin 20 per cent.

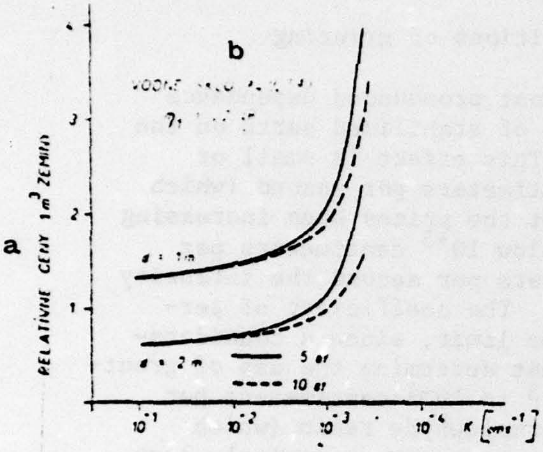

Figure 3. Dependence of the price of 1 cubic meter of stabilized earth (by 74 per cent waterglass) on the coefficient of permeability.

Key: a. Relative prices of 1 cubic meter of earth, b. waterglass 74 per cent.

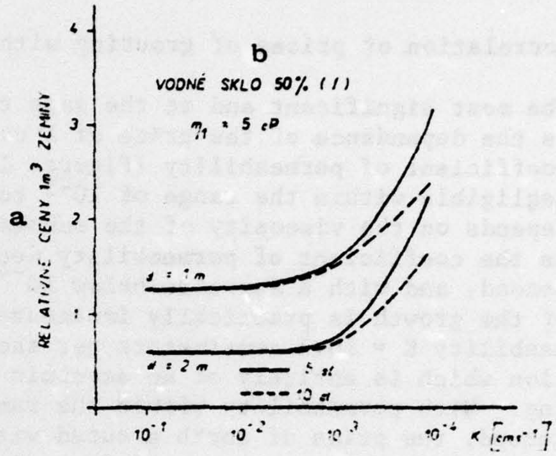

Figure 4. Dependence of the price of 1 cubic meter of stabilized earth (by 50 per cent waterglass) on the coefficient of permeability.

Key: a. Relative prices 1 cubic meter of earth, b. waterglass 50 per cent.

We assume that the earth with porosity n = 0.33 is fully saturated after grouting. In view of its anisotropy, we can assume that the injection material will be flowing approximately in the radial direction. After that, we shall determine the time needed for the grouting from the following simplified theoretical formula

$$T = 0{,}15 \frac{d^n}{Kh} \left(\frac{\eta_1}{\eta_0} \right)$$

where d is the distance of the drills,
K -- coefficient of permeability of the soil
h -- injection overpressure (height of the column),
$_1$ -- initial viscosity of injection material
$_0$ -- viscosity of water.

The given formula is used also in a changed form elsewhere in the planning of such injections (Barthel /3/). According to the measurements made by these authors, it gives about twice the actual value of T. This shortcoming is compensated by introducing only the values of initial viscosity in the formula, while the viscosity actually increases during the injection process. The exponent n in excess of value d is actually $2 \leq n \leq 3$, but for the same reason we take in consideration a lower value of $n = 2$.

Correlation of prices of grouting with the conditions of grouting

The most significant and at the same time the most pronounced dependence is the dependence of the price of 1 cubic meter of stabilized earth on the coefficient of permeability (Figures 1 to 4). This effect is small or negligible within the range of 10^{-1} to 10^{-3} centimeters per second (which depends on the viscosity of the substances), but the prices keep increasing as the coefficient of permeability decreases below 10^{-3} centimeters per second, and with a decrease below 10^{-4} centimeters per second the intensity of the growth is practically immeasurably high. The coefficient of permeability $K = 10^{-3}$ centimeters per second is the limit, since a consideration which is entirely of an economic nature must determine the use of grouting. With permeability within the range of 10^{-3} to 10^{-4} centimeters per second, the price of earth grouted with urea-formaldehyde resin (which means basic substance at a higher price) is lower than when seemingly less expensive waterglass is used for grouting. The given ratios will then be applicable also with regard to other grouting substances of higher quality (for example, in the case of resorcinol-formaldehyde resin). The coefficient of permeability $K = 10^{-4}$ centimeters per second is obviously the economic limit of the classic grouting, since the technical means used up to now will then be ineffective, even if we used pure water for grouting. That is how we should evaluate the data concerning the use of AM 9 in the earth with a coefficient of permeability $K < 10^{-4}$ centimeters per second (Flatau and collective /8/).

These trends apply in general, but the economic limit shifts to lower values of the coefficient of permeability in proportion to the growth of viscosity of the grouting material.

A comparison of the prices of grouting substances (see Table 1) has only a very problematical value in terms of evaluating the effectiveness of grouting of less permeable soils. In Table 4, the authors compare the relative prices of 1 cubic meter of grouted earth as compared to a 20 per cent solution of urea-formaldehyde resin ($c = 1.00$) for the coefficient of permeability $K = 10^{-1}$, 10^{-2}, 10^{-3}, and 10^{-4} centimeters per second, and then the relative degrees of strength of the grouted earth under simple pressure during solidification of the substance in an environment of 100 per cent relative humidity and relative price of 1,000 liters of the basic injection substance. The given values apply to the distance of drills of 2 meters and injection pressure of 5 atmospheres.

Table 3. Characteristics of Typical Grouting Substances Under Study

1 Označenie	2 Hmota	3 Koncentrácia [%]	4 Viskozita cP	5 Pevnosť [kp/cm²] pri uložení		
				6 sucho	100 % r. v.	7 voda
a	MF	50	10	80÷95	45÷65	45÷65
b	MF	33	3,5	9÷14	8÷12	8÷12
c	MF	20	2,6	6÷10	6÷8	4÷6
d	8 vodné sklo	73	22	15÷20	12÷16	8÷10
e	vodné sklo	66	8,2	13÷20	5÷13	4÷7
f	vodné sklo	50	5,0	3÷7	2÷5	2÷5

Key: 1. Designation, 2. substance, 3. concentration in per cent, 4. viscosity cP, 5. strength (kiloponds per square centimeter) in storage, 6. dry environment, 7. water, 8. water glass.

Table 4. Effectiveness of Stabilization

1 Označenie	2 Relatívne ceny 1 m³ zainjektovanej zeminy s ohľadom na c pre K cm/s				3 Relatívne pevnosti v tlaku pri uložení za 100% vlhkosti s ohľadom na c	4 Relatívne ceny 1000 l injekčnej hmoty s ohľadom na c
	10^{-1}	10^{-2}	10^{-3}	10^{-4}		
a	1,80	1,82	2,08	3,10	7,8	2,21
b	1,36	1,37	1,37	1,39	1,64	1,57
c	1,00	1,00	1,00	1,0	1,0	1,00
d	1,02	1,12	2,04	5,77	2,0	1,01
e	0,96	0,98	1,26	2,38	1,3	0,93
f	0,92	0,92	1,05	1,56	0,5	0,86

Key: 1. Designation, 2. relative prices of 1 cubic meter of grouted earth with regard to c for K centimeters per second, 3. relative resistance to pressure when stored under conditions of 100 per cent humidity with regard to c, 4. relative prices of 1,000 liters of the grouting substance with regard to c.

It is obvious that the price ratio of the basic grouting substance corresponds to the prices of stabilized earth only when the coefficient of permeability is K = $10^{-1} \div 10^{-2}$ centimeters per second. When less permeable earths are grouted, these ratios are disturbed, and at 10^{-3} centimeters per second they apply only in exceptional cases. At 10^{-4} centimeters per second, they do not apply any more at all. The need for a complex approach in evaluating the effectiveness of grouting is even more obvious, when one compares the prices of stabilized earth and degree of stabilization.

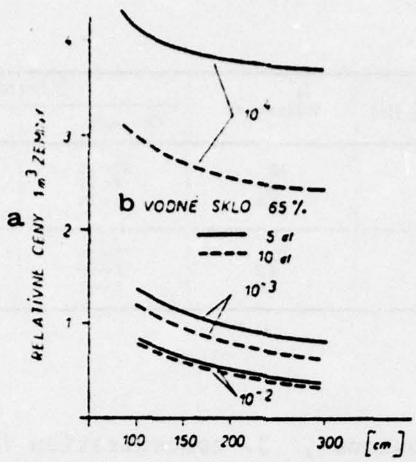

Figure 5. Dependence of the price of 1 cubic meter of stabilized earth (stabilized by 65 per cent of water glass) on the distances of drills.

Key: a. Relative prices of 1 cubic meter of earth, b. water glass.

In these cases, we separated the economic cases of the problem from the technical aspects. That is why we are comparing only injection substances which are administered technically (especially rheologically) in a similar way, but which we would replace with other substances, especially those based on cement, in the area of 10^{-1} to 10^{-2} centimeters per second. Generally speaking, these graphs would apply for example in the case of a very aggressive environment.

The effect of the distance between the drills is in all cases similar to the one shown in Figure 5. Within the range of $d = 1 \div 2$ meters, the price decreases as the distance of the drills increases, a further increase of the distance in excess of 2 meters is basically less pronounced, but at $K = 10^{-4}$ centimeters per second and more of viscosity of the substance, further increase of the distance of the drills results again in an increase of the costs. The significance of this statement is small in practice. It is mainly a question of expressing a trend. This conclusion concerning the distance of the drills is corrected to a great extent by data on time needed for grouting of individual stages as given in Table 5. Viscosity, pressure, and permeability influence the time of grouting linearly, while the distance of the drills influences it at least quadratically. This means essentially that earth with $K = 10^{-4}$ centimeters per second can be grouted only from drills made at a distance of 1 meter and in the case of substance with maximum viscosity 5 cP, while earth with $K = 10^{-3}$ centimeters per second can be grouted also from drills at a distance of 2 meters, but this action is effective when viscosity is at the most 10 to 15 cP.

The injection pressure is not reflected in practice in the cost in the case of earth with a coefficient of permeability greater than 10^{-3} centimeters per second (Figures 1 to 4). In the case of earth with $K = 10^{-3}$ centimeters per second the effect of the pressure on the cost is significant, and the cost increases as the substance is more viscous. Basically, one can state that earth with $K = 10^{-3}$ centimeters per second can be grouted in practice only by means of higher pressures, but that assumes such standard stress in the earth which would prevent "claquage." The critical standard stress in earth reaches here approximately the value of geostatic pressure (but the pressure may be also lower) and so it is generally questionable as to whether it is appropriate and possible to grout such earths by using the classic methods, if their depth does not exceed 20 to 30 meters.

Table 5. Time of Grouting (h) at a Pressure of Five Atmospheres

d[cm]	K [cm/s]	a Viskozita hmoty cP			
		2,6	5,0	10	2,2
100	10^{-3}	0,75	1,5	3,0	6,7
	10^{-4}	7,5	15	30	67,5
200	10^{-3}	3,0	6	12	27
	10^{-4}	30	60	120	270

Key: a. Viscosity of the material cP.

Conclusion

The effectiveness of the grouting of earth can be evaluated only by comparing the costs (and possibly other indices such as proper costs and labor consumption) of a certain volume of grouted earth and the effect achieved (for example strength). The price of the injection material is a rather inappropriate index for these purposes.

The lower limit of effective grouting of earth is the coefficient of permeability $K = 10^{-4}$ centimeters per second. This applies to all grouting substances, but economic considerations determine the grouting substance under consideration when the earth has permeability of less than 10^{-3} centimeters per second. These types of earth can be grouted only by means of higher pressures and by using grouting substances with a lower degree of viscosity, and consequently one must expect in this case a lower degree of stabilization as compared to permeable earths.

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